SCIENCE FOR GLASS PRODUCTION

UDC 666.1.031

PERFECTING THE TECHNICAL CHARACTERISTICS OF GLASS-MAKING FURNACES (REVIEW)

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Translated from *Steklo i Keramika*, No. 7, pp. 3 – 12, July, 2008.

The process of improving the main technical characteristics of a glassmaking furnace is examined: production capacity, specific throughput of the glass mass, and specific consumption of heat for glassmaking. It is shown that these characteristics are intercoupled and interdependent. The heat balance method is used to investigate the dependence of the specific consumption of heat on a number of parameters of the thermal operation of a furnace. It is recommended that the heat balance method be used at the initial stage of designing glassmaking furnaces.

Given the diversity of glass products and methods for manufacturing them, every glassmaking furnace should be regarded as a specially designed (novel) object. Prolonged continual operation makes it impossible to upgrade a furnace during the period between repairs. Consequently, when a design concept for a furnace is being developed, modern trends in furnace construction, improvement of the basic characteristics and their intercoupling, as well as the technical possibility and economic desirability of attaining prescribed efficiency parameters must all be taken into account. In other words, the objective conditions for maintaining competitiveness of the final product during the entire period of furnace operation must be incorporated in the goal set for a project.

For glassmaking furnaces, the goal of a design is to solve a multivariant problem with a large number of variables, many of which are intercoupled and cannot be measured directly. Thus, the production capacity of a furnace is determined not only by its construction but also by the organization of the heat-exchange processes in the flame space and in the melting tank. The specific fuel consumption depends on the specific throughput of the glass mass, flame arrangement, efficiency of the thermal insulation of the refractory masonry, operation of the regenerative heater, and other factors. The specific throughput of the glass mass, the temperature regime of melting, the quality of the refractory materials, and other factors all influence the furnace run. The parameters of the flame arrangement (direction, length, and so forth), the convection flows, the distribution of the melt temperature in the melting tank, the uniformity of the glass, and other characteristics cannot be measured and much less systematically monitored with instruments.

Under these conditions, to determine the goal of a design the technical characteristics, which together objectively reflect, as completely as possible, the technical and economic efficiency of a glassmaking furnace, must be prioritized. Such parameters, which are used in international practice, include the following: production capacity, specific consumption of heat for making glass, specific throughput of the glass mass, and the total production of glass per 1 m^2 of the melting tank area for a furnace run. It must be acknowledged that many problems facing our domestic glass industry largely arose not only because of a lack of competition between producers and the low cost of natural resources but also because of inaccurate analysis of the design objectives. As a result, the industry chronically lags behind the leading foreign producers of glass products both with respect to production capacity and the technological efficiency [1, 2]. Thus, Academician P. D. Sarkisov reported at the international summit "Steklo-2007" ("Glass-2007") that the average energy-intensiveness of glassmaking is 50% and sometimes 100% higher than in European glass works [3].

The external conditions for the operation of glass works have changed fundamentally over the last few decades. Market competition is tough. The cost of materials and fuel – energy resources is increasing continually. In the near future

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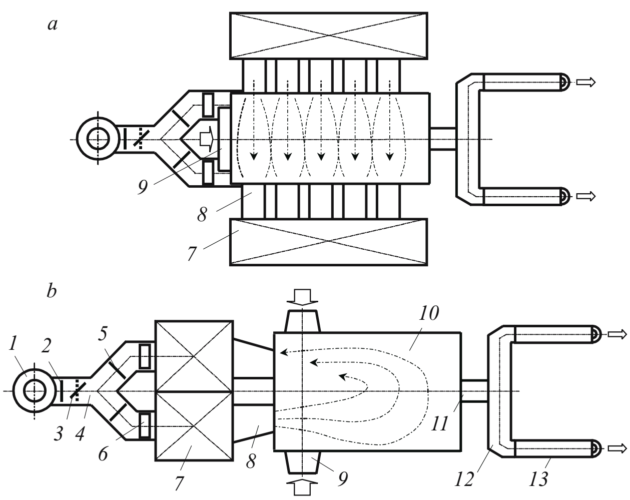

Fig. 1. Scheme of a glass container furnace with transverse (*a*) and horseshoe (*b*) flame arrangement: *1*) pipe; *2*, *3*) cut-off and rotating gate; *4*) flues; *5*, *6*) fine-adjustment and transfer gates; *7*) regenerative heater; *8*) burner facility; *9*) loading hopper; *10*) melting part of the furnace; *11*) flow channel; *12*) output channels; *13*) feed channel.

it will reach the price level of the world market, i.e., it will increase by a factor of 3 – 4. The capital intensiveness of modern glass production makes it impossible to recoup investments quickly; payback times are in the range 4 – 7 years. Under these conditions it is legitimate to focus attention on the highest technical level of efficiency indicators when the parameters for reconstruction or new production methods are being determined.

Choice of furnace design. At the present time, primarily heat-recovery tank furnaces which operate continually are used for mass production of commercial glass (flat and hollow). In general, the furnaces designed for making different types of container glass comprise 95% of all furnaces. For flat glass the fraction is 100%. Heat-recovery tank furnaces have not changed much externally over the last 10 years. At the same time, the main structural components of such furnaces have been continually upgraded.

As a result of improvements made in the melting and working tanks, burner facilities, heat-recovery system, and other components, the technical and economic performance of foreign furnaces has reached a very high level. It is sufficient to say that the efficiency of modern glassmaking furnaces exceeds 50 – 60%. The use of high-quality refractory and heat-insulation materials, modern systems for monitoring and controlling the thermal operation, and higher quality mineral raw materials and cullet used for preparing the charge have all facilitated the development of glassmaking furnaces [4, 5].

In domestic practice, there are examples of modern glassmaking furnaces which were developed, as a rule, by foreign engineering companies [6, 7]. At the same time, the industry possesses a large number of obsolete furnaces with low production capacity and high specific consumption of heat, which substantially decreases the industry-average technical efficiency of glass production.

Heat-recovery tank furnaces are divided into two types according to the motion of the products of fuel combustion in the working space.

Furnaces with a transverse flame (Fig. 1*a*) are used to make flat and container glasses. For flat glass, there is no alternative at present for this variant of a furnace design. Burning fuel by means of several pairs of burners positioned in the lateral longitudinal walls of the flames space makes it possible to implement a multistage technological glass production process quite effectively. Here, at each stage, flowing successively in time and space (along the melting tank), the required temperature, pressure, and gas composition can be created in the flame space.

Furnaces with a transverse flame are still used in the domestic glass-container industry. Such furnaces are even designed for new plants equipped with modern glass-forming equipment. In the opinion of the authors of these designs, this scheme makes it possible to solve the problem of achieving high production capacity (200 – 300 tons/day) with a lower risk by increasing the dimensions of the furnace. This neglects the fact that the extensive approach to the problem of production capacity inevitably results in a larger furnace, where the area of the melting tank can reach 150 – 200 m^2. In practice, this means that low-capacity float-process furnaces are used to make container glass.

At the same time, foreign and domestic experience shows that for making container glass with realistic production capacity (50 – 450 tons/day) it is more effective to use a heat-recovery glassmaking furnace with a horseshoe flame arrangement (Fig. 1*b*). In spite of the apparent difficulty of controlling its heat regime, this furnace design has a number of obvious advantages over the transverse heating scheme. For example, because of the smaller volume of the refractory masonry of the regenerative heaters and flue channels, the number of burners and charge loaders, monitoring sensors, and local systems for automatically controlling the heat regime, its cost is 20 – 30% lower than that of a furnace with a transverse flame arrangement. Other conditions being the same, the specific fuel consumption in furnaces with a horseshoe flame is 15 – 25% lower than in furnaces with transverse heating. This is due to smaller heat losses through the entry arcs and loading hoppers (by a factor of 3 – 5) and longer zones with heat transfer between the products of combustion and the surface of the tank (by a factor of at least 2) [8, 9].

It is obvious that the information presented above constitutes a quite weighty argument when choosing the construction of a furnace for making container glass. Glassmaking furnaces with a horseshoe flame, where the area of the melting tanks is 30 – 160 m^2, are now being used. These values are thought to be definite limits for furnaces of this type. Increasing the area of the tank above these values makes it more difficult to control the thermal operation of a furnace.

TABLE 1.

Bottle parameters	Production capacity, tons/day								
	IS-6		IS-8		IS-10		IS-12, DG	IS-8 + IS-8, DG	IS-10 + IS-10, DG
	DG*	TG*	DG	TG	DG	TG			
Capacity 0.5 dm^3, mass 320 g	52	78	70	104	87	130	104	140	174
Capacity 0.75 dm^3, mass 650 g	62	–	83	–	104	–	124	165	207

* DG and TG) two-and three-drop feed, respectively.

This also determines the minimum area of the melting tank in furnaces with a transverse flame, which, as a rule, is at least 70 m^2. The conventional limits on the minimum size of a tank is in no way reflected in the possibilities of increasing the production capacity of furnaces with a transverse flame, since the goal is achieved by increasing the specific throughput of the glass mass.

Production capacity of glassmaking furnaces. Advances in the glass industry today require continually increasing the production capacity of furnaces. This trend is characteristic for the production of flat and hollow glass (Fig. 2). It objectively reflects the state and development of the market for glass products. The widespread use of the progressive float method for obtaining flat glass (formation and thermal polishing of glass on the surface of a metal melt) requires furnaces with production capacity 400 – 1000 tons/day. Furnaces with lower production capacity, intended for producing flat glass by the vertical drawing method, are still in use. However, the fraction of furnaces with high production capacity will increase as obsolete vertical glass drawing systems are taken out of operation.

Similar trends are also seen in the production of hollow glass. This is due to the replacement of rotor glass-forming equipment by high production capacity lineal-sectional (IS) machines (Table 1). Modern systems for producing piecework can consist of several technological lines, equipped with IS machines. The most typical combination of glass-forming machines is presented in Table 2. Furnaces with production capacity exceeding 200 tons/day are required to feed the glass mass in such complexes. According to data provided by the Horn Company, furnaces with production capacity above 200 tons/day which are now being designed comprise more than 48% of all furnaces and the trend is upward [6].

Setting the nominal production capacity of a glass-making furnace appears, at first glance, to be a quite simple problem. It is known that it is determined by the rate of operation of the production equipment and the parameters of the product. For example, for the float process the furnace capacity is calculated as

$$P_{\mathrm{f}} = 0.024 w_{\mathrm{r}} \rho_{\mathrm{gl}} bd,$$

where P_{f} is the production capacity of the furnace, tons/day; w_{r} is the drawing rate of the ribbon, m/h; ρ_{gl} is the density of

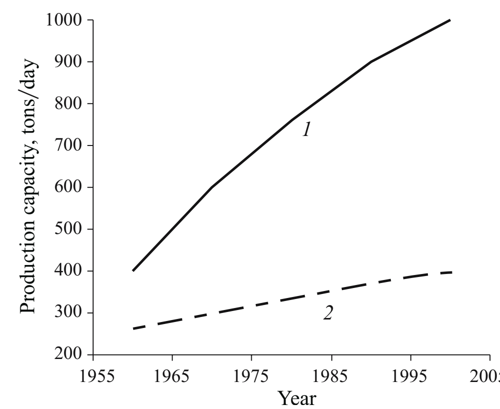

Fig. 2. Variation of the production capacity of glassmaking furnaces for producing flat (*1*) and hollow (*2*) glass.

the glass, kg/m^3; and, b and d are, respectively, the width and thickness of the glass ribbon, m.

The drawing rate depends on the width and thickness of the ribbon in a definite manner. For example [10], for $b = 3.5$ m and $d = 1.5$, 4, and 6 mm the drawing rate is 1500, 900, and 600 m/h, respectively. Furnace capacity 472.5 and 756 tons/day corresponds to these conditions.

The speed of operation of the IS machines depends on the geometric dimensions, the complexity of the shape, and the mass of the article. The formation method affects it to a definite extent. For hollow glass produced on linear-sectional IS machines the furnace capacity is calculated using a rela-

TABLE 2.

Composition of the complex	Production capacity, tons/day	
	maximum	minimum
IS-8 (DG), 3 pieces	250	210
IS-10 (DG), 3 pieces	310	260
IS-10 (TG), 2 pieces	280	260
IS-12 (DG), 2 pieces	250	210
IS-12 (DG), 3 pieces	370	310
IS-8 (DG), 2 pieces + IS-12 (DG), 1 pieces	450	380

tion that takes account of the type of production and the number of lines installed:

$$P_{\mathrm{f}} = 1.44\sum_{i=1}^{n}(w_{\mathrm{fg}}\, kmN)_i,$$

where w_{fg} is the feed rate of the glass mass (number of cuts per minute per section); n is the number of machines; i denotes the parameters of the ith machine; k is the number of drops; m is the mass of an article, kg; and, N is the number of sections.

The data in Table 1 show that the production of articles with different mass results in strong fluctuations of the production capacity of the furnace — 10 – 16% of the nominal value. Two extreme viewpoints concerning this problem can be formulated: on the basis of market priorities, it should be adopted as an unavoidable given or an assortment of products should be planned with no substantial change in the production capacity of the furnace. In either approach, two questions remain open: setting the nominal production capacity of a furnace and controlling the thermal operation of the furnace in transitional regimes.

If a furnace is planned for the maximum required production capacity, then when the production capacity is decreased we initially admit the possibility of operating a thermal unit with elevated specific consumption of fuel. An orientation toward the minimum throughput of the glass mass can limit the operation of the furnace when a “heavy” product assortment is manufactured. The need to turn to characteristics such as the nominal design production capacity of a furnace with the possibility of changing it by, for example, ± 10%, comes to mind. In this approach the deviation of the furnace production capacity from the average value will be reflected to a lesser extent on its technical performance.

We shall now consider the technical aspects of the thermal operation of a furnace with variable production capacity, understanding which could be helpful in overcoming the consequences of transient operating regimes. We start with a “simple” relation — the prescribed production capacity of the furnace should correspond to the prescribed glassmaking temperature (the temperature curve in the flame space). A deviation of the furnace production capacity from the nominal value requires changing the temperature conditions of glassmaking. The temperature in the furnace can be controlled by different methods [11 – 13]. The best understood methods are stabilization of the maximum temperature in the flame space by changing the fuel consumption and stabilization of the fuel consumption with by compensating the external actions on the temperature regime of the furnace. Both methods can be implemented only if transfer functions (regression equations) relating the production capacity of the furnace with the glassmaking temperature are available. Since, as a rule, glass producers do not possess such information, a new temperature regime for glassmaking is set experimentally, based on visual monitoring of the melting of the charge on the surface of the glass mass and on the quality of the finished product — in other words, by trial and error.

The temperature distribution along the flame space of the furnace with a horseshoe flame depends to a large extent on the length of the flame, which is determined by the fuel burn conditions. Changing the production capacity of a furnace requires correcting its heat load. The latter is reflected on the temperature and the volume of the outgoing products of combustion and, in consequence, on the air heating temperature. Therefore, to stabilize new temperature conditions for glassmaking every change in the fuel consumption and the associated change in the air heating temperature must be accompanied by a readjustment of the burners with mandatory monitoring of the fuel combustion quality, the flame length, and the position of the temperature maximum on the surface of the glass mass. If chemical analysis of the outgoing gases does not present any technical difficulties, then the evaluation of other parameters by means of instruments is impractical.

A variable production capacity and unstable conditions for external heat transfer during a transient period of furnace operation results in a change of the temperature field on the surface of the glass mass and the capacity of the working melt flow. In this case, the main initial conditions for internal heat transfer and, which is especially important, for the hydrodynamics of the glass mass in the glassmaking tank change. The transformation of a melt flow pattern until a new steady regime is reached can raise substantial problems with finished product quality. A change in the enthalpy of the working flow of the glass mass at the entrance into the distributing channel makes these problems more acute. Consequently, the possibility of adapting to changing heat transfer conditions must be provided in the design of this part of the furnace and its system for automatic control of the temperature regime.

On the whole, it should be noted that a change of the production capacity of a furnace during operation introduces substantial perturbations into the thermal operation of the furnace. In order to have the ability to set new temperature conditions for glassmaking and to rapidly destabilize these conditions it is necessary to investigate in detail the influence of the production capacity of the furnace on the external and internal heat transfer parameters. Taking account of the structural and technological features of a glassmaking furnace, it becomes understandable that problems of such complexity can be solved only by using a numerical mathematical model of the furnace, taking account of its real geometric parameters and the thermophysical aspects of the technological process.

Specific throughput of the glass mass. If the production capacity of the furnace is determined by the production equipment, then its specific magnitude is an important technical characteristic of the construction of the thermal unit. In general, two indicators of the specific production capacity, which characterize the instantaneous value of the specific

throughout P_{sp} and the total glass production P_{sp}^{Σ} from 1 m^2 of the melting tank over the entire period of operation of the furnace, should be kept in mind:

$$P_{sp} = P_f / F_m \text{, tons/(m}^2 \cdot \text{day)}; \quad (1)$$

$$P_{sp}^{\Sigma} = P_{sp} \text{P, tons/m}^2, \quad (2)$$

where F_m is the area of the melting tank, m^2, and P is the time between furnace repairs, days.

Even though the dependence is direct, the parameters P_{sp} and P_{sp}^{Σ} have different meanings. The total magnitude of the specific throughput characterizes the total efficiency of the furnace construction and largely determines the budget and cost-effectiveness of the entire business project. The total magnitude of the specific throughput of the glass mass lies in the range $(3 - 6) \times 10^3$ tons/m^2 for domestic furnaces and $(8 - 10) \times 10^3$ tons/m^2 for foreign furnaces. The negligible magnitude of P_{sp}^{Σ} for domestic furnaces is due to their short run time and the low specific throughput of the glass mass. Until recently, the time between repairs for domestic furnaces was 5 years for hollow glass and 7 years for flat glass, and this was considered to be a great achievement. At the same time, for foreign furnaces this time period is 8 – 10 years and 10 – 12 years, respectively.

The data presented on P_{sp}^{Σ} and P make it possible to determine the average specific throughput of the glass mass for modern glassmaking furnaces. For glass container furnaces with the minimum values $P_{sp}^{\Sigma} = 8$ tons/m^2 and P = 8 years we obtain $P_{sp} = 2.74$ tons/($m^2 \cdot$ day), which is practically two times higher than the industry-average domestic specific throughput. We note that the value given for P_{sp} is not the highest indicator. Examples of foreign glass container furnaces operating with specific throughput above 3 tons/($m^2 \cdot$ day) are well known. It is obvious that such high values of P_{sp} require mandatory application of auxiliary electric heating (AEH) of the melt in the melting tank. For flat-glass furnaces, the difference in the values of P_{sp} is not so great: for $P_{sp}^{\Sigma} = 10$ tons/m^2 and P = 12 years the specific throughput of the glass mass should be 2.28 tons/($m^2 \cdot$ day). For the best foreign furnaces 2.28 tons/($m^2 \cdot$ day).

It should be noted that increasing the specific throughput of the glass mass is one of the main trends in the modern advances of glassmaking furnaces (Fig. 3). The uniqueness of this characteristic of a furnace lies in the fact that its value is determined not only by the dimensions and cost of the furnace but also by the heat energy consumed for glassmaking.

It is well-known that the high specific throughput of the glass mass becomes possible if the required amount of heat can be transferred into the melting tank (zone of the technological process) and the time required to complete the entire complex of physical – chemical reactions of glassmaking can be provided. Since radiative heat transfer plays the dominant role in high-temperature furnaces, the determined dependence of P_{sp} on the glassmaking temperature becomes completely understandable (see Fig. 3). This dependence was obtained on the basis of experimentally established dependences of the rate of formation of the primary melt on the temperature of the process. The higher the temperature in the tank, the less time is required for the main stages of glassmaking.

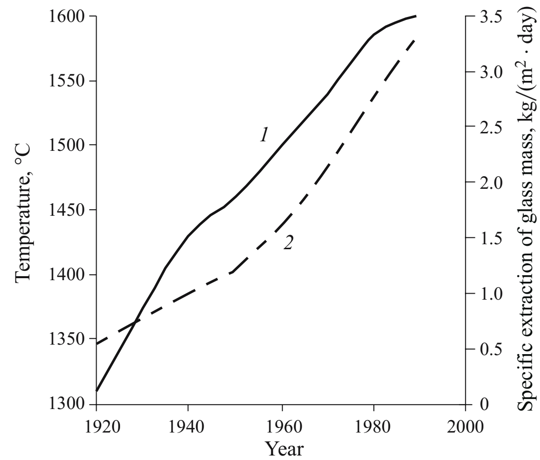

Fig. 3. Variation of the specific throughput of glass mass (*1*) and glassmaking temperature (*2*) — Garstang's curves.

As a result, by the end of the 20th century, the glassmaking temperature, which is the maximum masonry temperature monitored with instruments (for example, the crown of the flame space), reached essentially the maximum values for dinas refractories (1580 – 1600°C) used for the crown masonry. The desire to increase the specific throughput further by increasing the glassmaking temperature led to the use of electromelted AZS articles with lower glass-phase content, whose use with the admissible operating temperature 1640 – 1650°C makes it possible to increase the specific throughput by 0.15 tons/($m^2 \cdot$ day) for each 10°C the temperature is raised from the level 1600°C, for the crown masonry.

A great deal of attention has always been devoted in the domestic theory and practice of glassmaking to increasing the glassmaking temperature. Moreover, this factor is regarded as the main method for increasing the production capacity of furnaces [14 – 19]. The paradox lies in the fact that when the maximum glassmaking temperature was reached (1580 – 1600°C) domestic glass producers could not reach the corresponding specific throughput of the glass mass. In the production of hollow and flat glass, the average specific production capacity in the best case approaches 2 tons/($m^2 \cdot$ day). The reason for the mismatch between the glassmaking temperature and the specific throughput of the glass mass in domestic furnaces is that intensification of the thermophysical processes involved in glassmaking must be regarded as a multifactor phenomenon which depends on a host of thermal and technological parameters.

Specific consumption of heat for glassmaking. The consumption of the energy required is the most important operational characteristic of glassmaking furnaces. In practice, it is conventionally evaluated by the specific consumption of heat for making 1 kg of glass. In foreign countries with an advanced glass industry (USA, England, France, Germany, and others) the specific consumption of heat on making flat and container glass is, on average, 5.85 and 5.0 MJ/kg, and in the best furnaces — 5.1 and 4.33 MJ/kg, respectively. In the domestic glass industry, these indicators with rare exceptions [7, 20, 21] are 1.5 times higher than the level achieved in the world. In general form, for flame furnaces

$$q_{\mathrm{sp}} = \frac{BQ_1^{\mathrm{w}}}{P_{\mathrm{f}}}, \tag{3}$$

where q_{sp} is the specific consumption of heat, kJ/kg, B is the consumption of fuel, $\mathrm{m^3/sec}$, Q_1^{w} is the lowest working heat density of the fuel, $\mathrm{kJ/m^3}$, and P_{f} is the production capacity of the furnace, kg/sec.

It follows from Eq. (3) that for constant furnace production capacity q_{sp} is determined by the fuel consumption. We shall use the heat balance method to examine the specific heat consumption in glassmaking as a function of the main parameters of the thermal operation of the furnace. The heat balance of a glassmaking furnace is set for the glassmaking part in 1 sec (see Fig. 1). On the left-hand side, along the gas space, it is bounded by the output sections of the air channels of the burners, along which the products of combustion flow into the regenerative heater, and on the right-hand side, along the glass mass, it is bounded by the input section of the channel, along which the glass mass flow from the melting tank into the production channel. For a continuous action gas glassmaking furnace, the mechanical undercombustion of fuel Q_4 and the accumulation of heat in the masonry Q_6 are excluded from the classical structure of the heat balance equation. Since the quantities are relatively small, the physical heat of the charge and the cullet can be neglected. Under these assumptions the heat balance equation is

$$B(Q_1^{\mathrm{w}} + q_{\mathrm{a}} + q_{\mathrm{f}}) = Q_1 + B(q_2 + q_3) + Q_5 + Q_{\mathrm{neg}}, \tag{4}$$

where $q_{\mathrm{a}} = c_{\mathrm{a}} t_{\mathrm{a}} L_\alpha$ is the physical heat of the recovery air (per unit fuel), $\mathrm{kJ/m^3}$; $q_{\mathrm{f}} = c_{\mathrm{f}} t_{\mathrm{f}}$ is the physical heat of the fuel (gas), $\mathrm{kJ/m^3}$; Q_1 are the consumption of fuel, kW; $q_2 = c_{\mathrm{d}} t_{\mathrm{d}} V_\alpha$ is the physical heat of the products of combustion, $\mathrm{kJ/m^3}$; $q_3 = 0.02Q_1^{\mathrm{w}}$ are the heat losses due to chemical underburning of a unit of fuel, $\mathrm{kJ/m^3}$; Q_5 is the total loss of heat into the surrounding medium, kW; $Q_{\mathrm{neg}} = 0.1(Q_1 + Q_5 + Bq_3)$ are the neglected losses of heat, kW; t_{a}, t_{t}, and t_{d} are the temperature of the air, gas, and products of combustion, respectively, °C; c_{a}, c_{g}, and c_{d} are the average volume specific heat of the air, gas, and products of combustion in the temperature interval $0 - t$, respectively, $\mathrm{kJ/(m^3 \cdot K)}$; L_α and V_α are, respectively, the actual consumption of air for combustion and products of combustion (per unit fuel), $\mathrm{m^3/m^3}$.

We shall now show the contents of the quantities appearing in Eq. (4) for a furnace with a horseshoe flame. First, we calculate Q_1:

$$Q_1 = Q_{1,1} + Q_{1,2},$$

where $Q_{1,1}$ and $Q_{1,2}$ are the consumption of heat for the physical – chemical reactions involved in glassmaking, kW, and the heat of the production flow of the glass mass, kW.

For a prescribed furnace production capacity P_{f} (kg/sec)

$$Q_{1,1} = P_{\mathrm{f}}[G_{\mathrm{ch}}(q_\Sigma + \Sigma q_i) - q_{\mathrm{ph}}];$$

$$\Sigma q_i = q_1 + q_2 + q_3, \text{ kJ/kg},$$

where G_{ch} is the consumption of charge per 1 kg of glass mass, kg/kg; q_Σ is the total heat effect of the glass formation reactions per 1 kg of charge, kJ/kg; q_{ph} is the physical heat of the charge and the cullet, consumed to obtain 1 kg of glass mass, kJ/kg; and, q_1, q_2, and q_3 are, respectively, the consumption of heat for vaporizing moisture, heating the products of degassing, and melting glass, respectively, kJ/kg.

We shall dwell in the calculation of $Q_{1,2}$, which is included in the useful heat consumption because the enthalpy of the production flow is the main source of heat in the output channel where the last stage of glassmaking occurs — cooling of the melt to the temperature of the transition into the feed channel of the machine. The heat of the production flow of the glass mass is calculated as

$$Q_{1,2} = c_{\mathrm{gl}} t_{\mathrm{gl}} P_{\mathrm{f}},$$

where c_{gl} is the average specific key to the glass mass in the temperature interval $0 - t_{\mathrm{gl}}$, kJ/(kg · K), and t_{gl} is the temperature of the glass mass at the entrance into the flow channel, °C.

In general, the total heat losses through the furnace masonry can be represented in the form

$$Q_5 = Q_{5,1} + Q_{5,2} + Q_{5,3} + Q_{5,4},$$

where $Q_{5,1}$, $Q_{5,2}$, $Q_{5,3}$, and $Q_{5,4}$ are the losses of heat by conduction through the refractory masonry, by radiation through the inlets of the air channels of the burners, the arcs of the loading hoppers, and the opening of the viewing windows, respectively, kW.

In turn,

$$Q_{5,1} = \sum q_{5,1i} F_i,$$

where $q_{5,1i}$ is the density of the heat flux through the ith element of the furnace masonry, $\mathrm{kW/m^2}$, and F_i is the surface area of the ith element of the surface masonry, $\mathrm{m^2}$.

The stationary – cyclic temperature regime of the flame space of a glassmaking furnace makes it possible to use the

TABLE 3.

Heat balance	kW	%
Heat inflow items		
Chemical heat of fuel BQ_1^{w}	12,287.6	65.06
Physical heat of:		
air Q_{a}	6581.3	34.85
fuel Q_{f}	16.6	0.09
Total	18,885.5	100
Heat consumption items		
Useful heat consumption Q_1	7091.6	37.55
Heat losses:		
with products of combustion Q_2	9102.1	48.20
with chemical undercombustion of fuel Q_3	245.8	1.30
through furnace masonry Q_5	1556.5	8.24
Neglected losses Q_{neg}	889.4	4.71
Imbalance	0.1	0.0005
Total	18,885.4	100

equation of stationary heat conduction to calculate $q_{5,1i}$. If the temperature of the inner surface of the masonry is known, then we have

$$q_{5.1i} = \frac{t_{\mathrm{in}} - t_{\mathrm{sur}}}{\sum\limits_{i=1}^{i=n} \frac{S_i}{\lambda_i(t)} + \frac{1}{\alpha_{\mathrm{out}}}},$$

where t_{in} and t_{sur} are, respectively, the temperature of the inner surface of the masonry and of the surrounding medium ($t_{\mathrm{sur}} = 30°\mathrm{C}$); S_i is the thickness of the ith layer of the masonry, m; $\lambda_i(t)$ is the temperature dependence of the thermal conductivity of the ith layer, W/(m · K); α_{out} is the total heat emission coefficient, W/(m^2 · K); and, n is the number of layers.

We now substitute into Eq. (4) the content of some of its components and solve it for B:

$$B = \frac{1.1Q_1^{\mathrm{w}}(Q_{1,1} + c_{\mathrm{gl}} t_{\mathrm{gl}} P_{\mathrm{f}} + Q_5)}{0.978Q_1^{\mathrm{w}} + c_{\mathrm{a}} t_{\mathrm{a}} L_{\alpha} + c_{\mathrm{f}} t_{\mathrm{f}} - c_{\mathrm{d}} t_{\mathrm{d}} V_{\alpha}}. \quad (5)$$

We now replace the left-hand side of the expression (5) using Eqs. (1) and (2), and after simple manipulations obtain

$$q_{\mathrm{sp}} = \frac{1.1Q_1^{\mathrm{w}}(Q_{1,1} + c_{\mathrm{gl}} t_{\mathrm{gl}} P_{\mathrm{f}} + Q_5)}{P_{\mathrm{sp}} F_{\mathrm{a}}(0.978Q_1^{\mathrm{w}} + c_{\mathrm{a}} t_{\mathrm{a}} L_{\alpha} + c_{\mathrm{f}} t_{\mathrm{f}} - c_{\mathrm{d}} t_{\mathrm{d}} V_{\alpha})}. \quad (6)$$

The expression (6) makes it possible to examine clearly the influence of certain parameters of the thermal operation of the furnace on its thermal cost-effectiveness: $q_{\mathrm{sp}} = f(t_{\mathrm{a}})$, $q_{\mathrm{sp}} = f(t_{\mathrm{gl}})$, $q_{\mathrm{sp}} = f(t_{\mathrm{d}})$, $q_{\mathrm{sp}} = f(Q_5)$, and $q_{\mathrm{sp}} = f(P_{\mathrm{sp}})$. Similar relations can be written for the efficiency of the furnace: $\eta_{\mathrm{eff}} = Q_1/BQ_1^{\mathrm{w}}$. Naturally, the analysis of the relations presented will be more qualitative than quantitative, since essentially all arguments of the functions are interrelated. To use Eq. (6) for analysis it is necessary to set a basic situation where the parameter of interest will change with all other parameters remaining constant.

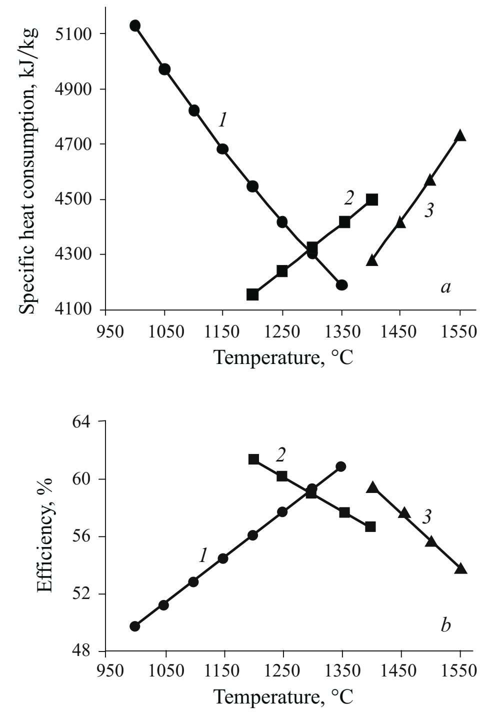

Fig. 4. Effect of the heating temperature of the air (*1*), production flow of the glass mass (*2*), and products of combustion (*3*) on the specific consumption of heat for glassmaking (*a*) and furnace efficiency (*b*).

We shall use the results of a calculation of the heat balance of a glassmaking furnace with production capacity 240 tons/day and a horseshoe flame, intended for making green glass (Table 3). The additional initial data are: $Q_1^{\mathrm{w}} = 34898$ kJ/m^3, $Q_{1,1} = 2516.7$ kW, $t_{\mathrm{a}} = 1250°\mathrm{C}$, $t_{\mathrm{d}} = 1450°\mathrm{C}$, $t_{\mathrm{gl}} = 1355°\mathrm{C}$, $F_{\mathrm{m}} = 109.65$ m^2, and $P_{\mathrm{sp}} = 0.025347$ kg/(m^2 · sec). A characteristic feature of the data in Table 3 is that the construction of the masonry of the glassmaking part of the furnace was taken into account in detail in the heat balance of the furnace, and the results of numerical simulation were used to set the temperatures of the media participating in heat transfer [22 – 24].

Of the dependences presented in Fig. 4, only the functions $q_{\mathrm{sp}} = f(t_{\mathrm{a}})$ and $\eta_{\mathrm{EFF}} = f(t_{\mathrm{a}})$ are of any definite applied interest in the quantitative respect. Analysis of other dependences is qualitative, since the temperature of the combustion products and the working flow of the glass mass, as noted above, are a result of heat-transfer processes in the flame space of the furnace and the melting tank. The data in Fig. 4 illustrate the quite predictable effect of the heating temperature of the air, the temperature of the combustion

products, and the temperature of the working flow of the glass mass per unit consumption of heat on glassmaking and the efficiency of the furnace.

Let us consider the temperature of the glass mass. Even though the enthalpy of the output flow $Q_{1,2}$ is ordinarily considered to be a useful expenditure of heat, in reality only some of it is used for useful purposes. It includes the enthalpy of the glass mass at the entrance into the feed channels and the expenditure of heat to compensate for the losses through the masonry of the channel, coffer, and production channel. The excess heat of the output flow is forcibly removed into surrounding medium. For high efficiency furnaces, which are characterized by a high temperature of the glass mass at the exit from the melting tank (1250 – 1400°C), cooling the glass mass to the temperature of the entrance into the feed channel (1150 – 1200°C) is a quite complex engineering problem. Depending on the production capacity of the furnace, the thermal energy extracted can reach 5 – 15% $Q_{1,2}$. Consequently, the effect of the temperature of the production flow of the glass mass on the thermal efficiency of a glassmaking furnace is more important than an analysis of the thermal balance implies. Determination of the conditions under which the production capacity of a furnace is reached at the minimum value t_{gl} is one of the most difficult problems in modern heat-engineering of glassmaking. It is obvious that the solution to this problem is not limited to investigations of the external heat transfer; it requires a detailed analysis of the internal problem — heat transfer and hydrodynamics of glass melts in the melting tank.

It is quite difficult to minimize the temperature of the products of combustion at the exit from the flame space of the furnace, which depends directly on the flame arrangement and, on the whole, the external heat transfer. For a glassmaking furnace with a horseshoe flame, the determination of the optimal conditions for organizing the flame and the external heat transfer is inextricably related with the special features of the multistage technological process. The solution of the problem lies in making a compromise between burning fuel in a flame with the shortest length and the length for which the required temperature distribution of the glass mass along the melting tank is secured. This compromise can be expressed as the optimal flame length [25, 26]. It is obvious that the heat balance method and full-scale experimental investigations did not permit solving this problem.

It is well-known that the heating temperature of the air is determined by the area of the heating surface of the attachment and F_{att} and the enthalpy of the outflowing products of combustion, i.e., t_d. For a modern regenerative heater, characterized by $F_{att}/F_a = 35 - 45$ m^2/m^2, the following relation can be used: $t_d - t_a = \Delta t = 150 - 300$°C. The value of Δt is determined by the ratio F_{att}/F_a, which is directly related with the dimensions of the regenerative heater. Obviously, when choosing the dimensions of the heat-recovery chamber, it is helpful to have information about the quantitative relation between t_a, q_{sp}, and η_{EFF}. The equations presented below, which were obtained by fitting to the data in Fig. 4 (curve *1*), should be regarded as approximate and intended for primary valuation of the parameters of the thermal operation of a furnace:

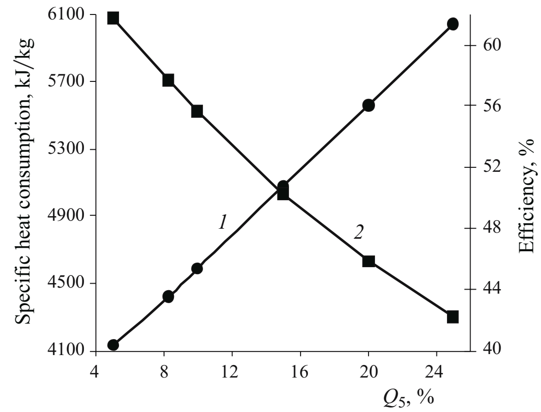

Fig. 5. Effect of heat losses through the masonry on the specific consumption of heat for glassmaking (*1*) and furnace efficiency (*2*).

$$q_{sp} = 9909.1 - 6.331 t_a + 0.001 t_a^2; \qquad (7)$$

$$\eta_{EFF} = 17.7 + 0.032 t_a. \qquad (8)$$

Analysis of the expressions (7) and (8) shows that increasing the heating temperature of the air by 100°C decreases the specific consumption of heat by 5.2% and increases the furnace efficiency by 6.4%. These results agree well with the practical data [27, 28]. It is noted in these works that increasing the heating of the air by 200 – 300°C makes it possible to decrease the specific consumption of fuel by 10 – 15%. At the same time, they are also comparable with the analytical data of [29, 30]. In the first of these works, the heating air by 100°C is rated as a decrease of y_{sp} by 6.0% and in the second work it is rated by an increase of furnace efficiency by 7%.

On the whole, the results of the analysis show that the heating temperature of the air has a large effect on the thermal operation of the furnace. At the same time, it can be stated that the heating temperature of air which has now been attained 1300 – 1250°C, just as the glassmaking temperature, is approaching its limiting value. If the construction of the regenerative heater and attachment can be improved, then the amount of heat flowing from the flame space of the furnace will limit the possibility of greater heating of the air.

Let us now consider the dependences $q_{sp} = f(Q_5)$ and $\eta_{EFF} = f(Q_5)$. In our view, Eq. (6) makes it possible to estimate quantitatively, quite accurately, the effect of the heat losses through the masonry on the thermal efficiency of the furnace. It follows from the data in Fig. 5 that decreasing the fraction Q_5 in the heat balance of the furnace by 1% makes it possible to decrease the specific consumption of heat and increase the efficiency of the furnace by approximately 2%. Undoubtedly, a decrease of heat losses through the masonry

has reached its physical limit, which, on the basis of the quality of modern refractories and heat-insulating materials, can be 5 – 8%.

We recall the complex structure of Q_5. In the example of heat balance presented above (see Table 3) the losses via heat conduction through the furnace masonry $Q_{5,1}$ are only 64.0%. Of this value, 25.2% represent heat losses through forcibly cooled sections of the outer surface of the melting tank, which can be referred to the so-called incompressible losses. The remaining losses (36.2%) are distributed as follows: $Q_{5,2} = 24.7\%$, $Q_{5,3} = 9.3\%$, and $Q_{5,4} = 2.0\%$. Thus, a decrease of the fraction of the losses through the furnace masonry is not only an improvement of the heat insulation of the masonry but also an improvement in the construction of the air channels of the burners and loading hoppers. As a matter of principle, it is important that an accurate calculation of this item of the consumption of heat presupposes a substantiated setting of the temperatures for all media participating in heat transfer.

Let us now consider the functions $q_{sp} = f(P_{sp})$ and $\eta_{EFF} = f(P_{sp})$, which most completely and comprehensively characterize the efficiency of the thermal operation on a glassmaking furnace. It follows from Eq. (1) that for the condition $P_f = \text{const}$ the deviation of the specific throughput from the base value presupposes a contribution which is inversely proportional to the change in the glass mass surface area. Correspondingly, the total surface area of the refractory masonry of the furnace and $Q_{5,1}$ also change. If it is assumed that for $P_{sp} = \text{var}$ the internal temperature of the masonry surfaces remains unchanged, then $Q_{5,1}$ can be adjusted using the specific heat losses through the masonry $Q_{5,1}/F_a = 9.08\ \text{kW/m}^2$. Taking account of the assumptions made, the quantitative expressions for the dependences considered here are

$$q_{sp} = 6573.9 - 2233.6P_{sp} + 789.23P_{sp}^2 - 99.678P_{sp}^3; \quad (9)$$

$$\eta_{EFF} = 34.833 + 22.481P_{sp} - 7.5247P_{sp}^2 - 0.9244P_{sp}^3. \quad (10)$$

Figure 6 displays a graphical representation of Eqs. (9) and (10) (curves *2* and *3*). The form of the dependences shows that qualitatively they correspond to the well-known form of the functions $q_{sp} = f(P_{sp})$ and $\eta_{EFF} = f(P_{sp})$. The quantitative adjustment of the expressions can be estimated using experimental data obtained on a furnace with a similar structure and approximated by the equation [20]:

$$q_{sp} = 8023.8 - 2173.2P_{sp} + 315.25P_{sp}^2. \quad (11)$$

Comparing the values of q_{sp} calculated from Eqs. (9) and (11) shows that the first one gives results which are too low. The largest deviation (18.4%) corresponds to $P_{sp} = 1\ \text{tons/(m}^2 \cdot \text{day)}$ and the lowest deviation (1.3%) corresponds to $P_{sp} = 3\ \text{tons/(m}^2 \cdot \text{day)}$. The average deviation of the calculation is 10%. The error in calculating the efficiency

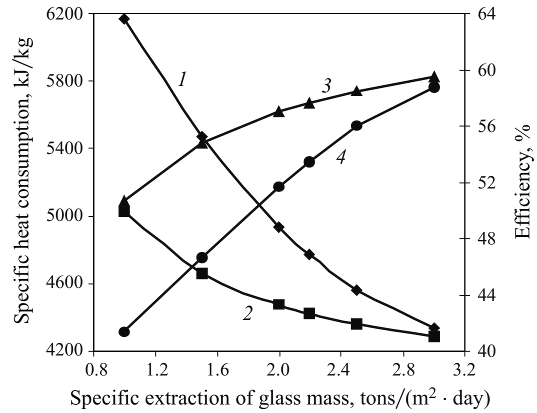

Fig. 6. Influence of the specific extraction of glass mass on the specific heat consumption for glassmaking (*1*, *2*) and furnace efficiency (*3*, *4*): *1*, *4*) experimental data; *2*, *3*) calculations.

of the furnace using the heat balance equation is 21.6 and 1.2%, respectively. The average computational error is 9%. For $P_{sp} = 2.19\ \text{tons/(m}^2 \cdot \text{day)}$, for which the heat balance is constructed, the underestimate of q_{sp} and overestimate of η_{EFF} are 7.4%. The computational error and the character of its dependence on the specific extraction of glass mass are completely explainable by the assumed constancy of the masonry temperature with $P_{sp} = \text{var}$, which cannot correspond to real operating conditions of a furnace. Analysis of the experimental data (Fig. 6, curves *1* and *4*) shows that increasing the specific glass mass throughput every $0.2\ \text{tons/(m}^2 \cdot \text{day)}$ makes it possible to decrease the specific consumption of heat by approximately 2% and increase furnace efficiency by 2.8%. Undoubtedly, increasingly specific production capacity is the most important factor in intensifying the thermal operation of a furnace.

Summarizing, we note that the main technical characteristics of a glassmaking furnace depend on one another. For example, the specific heat consumption for glassmaking is determined by many factors, the most important of which are the specific throughput of the glass mass, the heating temperature of the air for combustion, and the heat losses through the masonry. For thermal cost-effectiveness of the furnace, it is important to reduce the temperature of the products of combustion and the temperature of the working flow of the glass mass to a minimum.

A preliminary analysis of the characteristic changes in the main technical characteristics of the furnace at the rough design stage can be performed by using the heat balance method, taking great care in setting the boundary and initial conditions for the calculation. At the same time, the heat balance method does not permit determining the characteristics of heat transfer and hydrodynamics, which make it possible to determine the parameters of the thermal operation of the furnace that correspond to a prescribed production capacity. As noted previously [31], it is desirable to use numerical simulation to make a detailed investigation of the thermal

operation of a furnace. The initial base of boundary conditions, which is needed to develop and adapt a mathematical model (to a first approximation), can be obtained from the heat balance of the furnace.

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